Consideration of Real Fire Conditions While Calculating the Critical Fire Load Density in Compartments on the Basis of the Kinetic Approach

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ABSTRACT

This paper presents the theoretical background and an engineering calculation method for the determination of the maximum (critical) value of the fire load density for which a failure does not occur for the load bearing structures in a defined fire compartment when exposed to a simulated natural fire. The critical fire load density is suggested to be defined for real fire exposure on the structure on the basis of a kinetic approach. The use of the kinetic approach to solve this problem as well makes it possible to consider more precisely the real fire behaviour of the structure than when calculating on the basis of a static approach.

KEYWORDS: real fire, fire load, compartment,temperature state, load bearing capacity, structure.

INTRODUCTION

Under the real fire the structural fire behaviour depends greatly upon the value of the fire load density in a compartment. That is why, the structural fire behaviour of the building under the real fire exposure can be provided by limiting the fire load density in a compartment /6/.

In this connection the important problem of fire safety is the obtaining of the data concerning the maximum values of the fire load density in a compartment for which a failure does not occur for the load bearing structures in a defined fire compartment when exposed to a simulated natural fire.

The maximum value of the fire load density in a compartment for which a failure does not occur for the load bearing structures in a defined fire compartment when exposed to a simulated natural fire is proposed /1/ to be called "critical".

In papers /2-6/the use of static and kinetic approaches when calculating the structural fire behaviour for a real fire exposure was analyzed.

The static aproach means that static system of the bounded atoms of a solid body interacts with an external force. In the limits of this conception the material resistance depends on the correlation between the cohesion forces and external forces,influencing interatomic bonds /5/.

The introduction in static (mechanical) approach of the conception of "ultimate strength" and "limit temperature" of heating of the material reflects the critical nature of breaking the stability of such static system under heating with simultaneous action of external forces.

The corresponding change of structural strength under the conditions of high temperature heating is expressed /1/ as the function "strength -temperature" independent on time:

$$R = f\ (T) \tag{1}$$

or in the dimensionless values as follows:

$$m\ (T) = \frac{R(T)}{R} = f\ (T) \tag{2}$$

where R is the structural strength found by means of the standard mechanical tests under normal conditions,R (T) - the structural strength found by means of mechanical tests under the definite regime of heating.

The new opportunities of the development of the material strength and durability arise in connection with the appearance of the kinetic conception of the physical nature of strength and the destruction of solid bodies /5/.According to this conception the destruction is regarded as the real proressing in time process of the accumulation of damages and the durability of objects characterizes the period of their existence from the moment of applying the force till the moment of their destruction.

In the theory of fire resistance time is one of the principal characteristics of behaviour of building materials and structures under the conditions of fire exposure. The conception of "fire resistance limit" is equivalent to the conception of the durability of solid bodies referring to the specific conditions of fire. In reality "fire resistance limit" of building structures characterizes the "period of its existence from the moment of the fire appearance to the moment of arising its critical state /5/ that is "durability" under the conditions of fire.

In this paper, the use of a kinetic aproach for the calculation of the critical fire load density in a defined compartment based directly on a real fire exposure on structure is shown.

PHYSICAL MODEL

For a load bearing structure, the design criterion for an analytical determination of the critical fire load density in a compartment, based directly on a real fire exposure on the structural elements, implies that the fire load density q will be critical q^{cr}, when the minimum value of the load bearing capacity min $R(\tau,q)$ during the real fire exposure meets the load effect on the structure S, i.e.:

$$\min \{R(\tau,q)\} = S, \text{ then } q = q^{cr} \qquad (3)$$

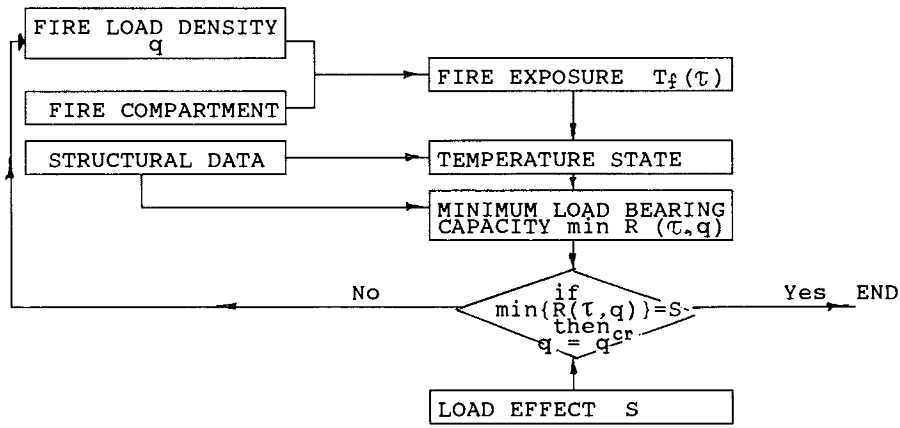

FIGURE 1. Physical model for an analytical engineering design of the critical fire load density in a compartment, based directly on a real fire exposure

The physical model for a structural fire engineering design is shown summarily in Fig.1.

The procedure can be subdivided into the following main steps (Fig.1): prediction of the compartment fire temperature -time curve on the basis of the fire load density and the fire compartment characteristics, the temperature-time fields in the structure, the load bearing capacity of the structure and a comparison between the minimum value of the load bearing capacity during the relevant fire process and the load effect S, according to equation (3).

To solve the problem of the determinaton of the critical fire load density of a given compartment is enough to test the design criteria (3) for the weakest structure in the compartment. Usually, such structures are the bending ones (slabs, beams, etc.).

For a reinforced concrete slab, the ultimate fire behaviour is defined by the deformation of the principal tensile reinforcement, the design criterion (3) based on the kinetic approach can be shown to be:

$$\max \{\varepsilon(\tau,q)\} = \varepsilon^{cr}, \text{ then } q = q^{cr} \qquad (4)$$

where: $\varepsilon(\tau,q)$ - the change of a complete slab principal reinforcement deformation depending upon the time of the real fire exposure and the fire load density in a compartment q ; ε^{cr} - critical value of the complete principal reinforcement deformation when time of failure under the fire takes place.

On the basis of the static approach design criterion (3) has the following form /1/:

$$\max \{T_s(\tau, q)\} = T_s^{cr}, \text{ then } q = q^{cr} \qquad (5)$$

where: $T_s(\tau, q)$ - the temperature change of the slab principal reinforcement depending on time of real fire exposure, regime of which under other equal conditions is defined by the fire load density value in a compartment : T_s^{cr} - the critical value of heating temperature of the slab reinforcement under fire when the time of failure has come.

CALCULATION METHOD

For an analytical determination of the critical fire load density in a compartment based on the physical model /in Fig.1/, one can use calculation methods described in /5,6/.

For the first step of calculation - the determination of the gas temperature in the compartment $T_f(\tau)$ at time (min) of fire exposure the following equations can be used:

$$\text{when } \tau \le \tau_m \quad T_f(\tau) = \Psi\, 345 \log(8\tau + 1) + T_o \qquad (6)$$

$$\text{when } \tau > \tau_m \quad T_f(\tau) = \Psi\, 345 \log(8\tau + 1) - V_c(\tau - \tau_m) + T_o \qquad (7)$$

where T_o - gas temperature of compartment at $\tau = 0$,°C; Ψ - coefficient of fire intensity, which expresses the ratio of gas temperature in compartment at any time of fire exposure to the temperature of the standard fire at the same time; τ_m - the time to reach the maximum gas temperature in the compartment T_f^{max}, min, in the real fire exposure; V_c - a parameter which characterizes the descending rate of the gas temperature in the compartment, °C/min.

Approximately, the folliwing equations apply for Ψ, τ_m, and V_c /5,6/

$$\Psi = 1.37 - \frac{150 K_{1,red} - 0,65}{(K_{1,red})^2\, 10000} \qquad (8)$$

$$\tau_m = \frac{60 q_{red}}{8318 K_{1,red} - 4021 (K_{1,red})^2} \qquad (9)$$

$$V_c = \frac{98000 K_{1,red} - 1500}{q_{red}} \qquad (10)$$

where $K_{1,red}$ - equivalent opening factor, $m^{1/2}$ /2,4,6/;
q_{red} - equivalent fire load density of the enclosures of the compartment, MJ/m^2 /2,4,6/.

The theoretical methods for the second step of calculation are described in paper /5,6/. They give the opportunity to solve, in a simple way, the thermophysical fire behaviour of structures with the consideration of real fire conditions on the basis of the principle of superposition.

The method of superposition allows the solution of a complex task to be broken down into several tasks which are less complicated. In this case, the two basic phases of the real fire exposure described by the compartment gas temperature (the heating phase and the subsequent cooling phase) are considered separately. Consequently the total fire exposure is considered to be the sum of two thermal actions, one positive and one negative.

To define the load bearing capacity of the structure under real fire conditions (the third step of calculation) the basic relations of a kinetic concept of critical strain are used, as well as the principle of a linear summation of damages and creep flow /5/. The calculation of the load bearing capacity of the structure,based on the static approach,described in /1/

RESULTS AND DISCUSSION

On the basis of the premises and methods described above, more than 160 combinations of the opening factor of the compartment, the fire load density and the structural characteristics have been computed in order to find the effect of the real fire exposure.The structure chosen is a reinforced concrete ceiing slab.*

Initinal data: the slab width -1.2m; the slab thickness - 0.2m; the thickness of concrete cover of the principal reinforcement = 0.015; 0.02; 0.025, 0.03 m; principal reinforcement 0.012m in diameter; the cross-section area of the principal reinforcement - 0.000452 m ; kinetic characteristics of reinforcement strength /5/ U_o= 286 kJ/mol, γ = 0.095 kJ/(mol MPa); concrete ρ = 2350kg/m ,R_b = 11MPa.
Compartment: opening factor K_1 = 0.02; 0.04;0.06;0.08;0.12 $m^{1/2}$ /2,4,6/.
The fire load density in the compartment q : 150 - 800 MJ/m^2 .
The bending moment from workloads M = 50700 Nm.

All variants of this task have been computed by 2 methods based on the static and kinetic /5,6/ approaches.

When appreciating the critical fire load density in a compartment on the basis of the static approach, the fire load density in a compartment is considered to be critical under design criterion (5), when T_s^{cr} = 492 °C.

When appreciating the value of the critical fire load density in a compartment on the basis of the kinetic approach,the fire load density in a compartment is considered to be critical under design criterion (4) when ε^{cr} = 0.044.

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* work was done with participation of M.A.Abdul Majeed

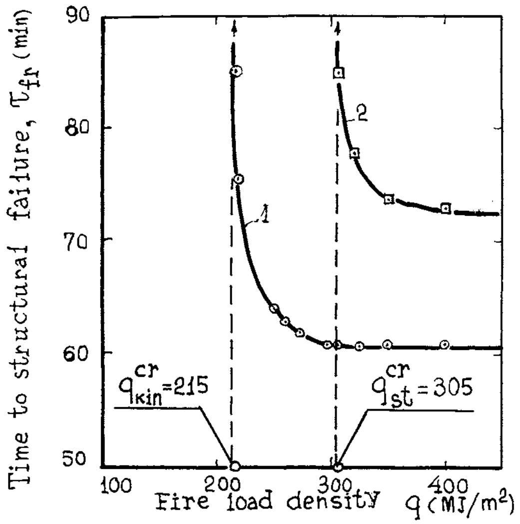

FIGURE 2. Typical diagram of the results from one design series giving the critical fire load density q in a compartment (K_1 = 0.04m$^{1/2}$),based on a real fire exposure on a reinforced concrete ceiling slab (δ= 0.025m). 1-kinetic approach application; 2-static approach application.

The computed results are illustrated by the following table and figures 2 and 3.

Figure 2 shows the calculated relationship between the fire load density q and the time to failure for a reinforced concrete slab with a specified concrete cover = 0,025m when reposed to a simulated real fire in a specified compartment with the opening factor 0,04 m$^{1/2}$ $\tau_{fr} \to \infty$ defines the critical fire load density q^{cr} below which no structural failure will occur.The two curves 1 and 2 relate to calculations based on the kinetic and static approaches,respectively.

Systematically performed calculations according to Figure 2 are summarized in the table, reporting the critical fire load densities according to the kinetic q^{cr}_{kin} and static aproaches q^{cr}_{st} for diferent combinations of the opening factor of the compartment and the concrete cover of the reinforced concrete ceiling slab.
In all diagrams similar to Fig.2,the values of the critical fire load density in a compartment obtained by the calculation on the basis of the static approach are more than q ,obtained by the calculation on the basis of the kinetic approach (see Table and Fig.2).

It shows that when solving the static tasks of fire resistance the underestimation of the real fire danger takes place since the value of the critical fire load density in a compartment that must provide the safety of all structures under the real fire is overvalued. It occurs because of the initial theoretical premises of static approach under which it is impossible to consider the changing strength and deformation properties of structural materials in the phase of cooling /5/

TABLE

The critical fire load density q^{cr} in specified compartments determined a real fire exposure on a reinforced concrete slab by kinetic and static approaches

Opening factor K ($m^{1/2}$)	Thickness of concrete cover δ(m)	q^{cr} (MJ/m^2)		$\Delta q^{cr} = q^{cr}_{st} - q^{cr}_{kin}$	$\Delta\% = \frac{\Delta q^{cr}}{q^{cr}_{kin}} 100\%$
		q^{cr}_{kin}	q^{cr}_{st}		
0.12	0.015	365	435	70	19.2
	0.02	420	520	100	23.8
	0.025	475	615	140	29.5
	0.03	525	710	185	35.2
0.08	0.015	265	320	55	20.7
	0.02	305	385	80	26.2
	0.025	340	455	115	33.8
	0.03	385	530	140	36.4
0.06	0.015	215	265	50	23.2
	0.02	245	320	75	30.6
	0.025	275	375	100	36.4
	0.03	305	440	125	41
0.04	0.015	165	215	50	30.3
	0.02	190	255	65	34.2
	0.025	215	305	90	41.8
0.02	0.02	115	160	45	39

The use of the kinetic approach for solving this task as well permits to consider all thermal history of the real fire exposure including the cooling phase of structure. During this phase the structures additionally lose the part of their load bearing capacity. That is why, the design values of the critical fire load density obtained on the basis of the kinetic approach are always less than the similar data obtained under the static calculation, that is $q^{cr}_{kin} < q^{cr}_{st}$.

To appreciate the possible underestimation value of the real fire danger when caculating the critical fire density in a compartment using the static approach, the computed results were treated by the formula: (see Table)

$$\Delta = q^{cr}_{st} - q^{cr}_{kin} / q^{cr}_{kin} \cdot 100\% \qquad (11)$$

where: q^{cr}_{kin} - the value of the critical fire load density in a compartment obtained by more precise calculation on the basis of the kinetic approach; q_{st}^{cr} - the critical fire load density in a compartment obtained by the static calculation without considering the phase of fire decay.

The Table data are shown in Fig.3 in the form of dependence Δ (δ ,K_1).

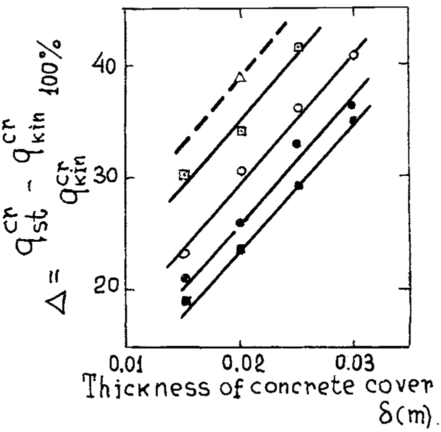

FIGURE 3. Dependence of possible underestimate Δ % of value of the critical fire load density q^{cr} in compartments on the opening factor K_1 and the thickness of concrete cover δ on the effect of the real fire exposure on the reinforced concrete slab by the static approach application.
1-K_1=0.02; 2-0.04; 3-0.06; 4-0.08; 5-0.12 ($m^{1/2}$).

The diagram in Fig.3 shows that the level of possible underestimation of the real fire danger under static calculation of the critical fire load density in a compartment may constitute more than 38-40%.

CONCLUSIONS

Thus, the use of the kinetic approach to solve the various problems of fire safety connected with the structural behaviour under the real fire makes it possible to consider the special features of the real fire exposure more precisely and completely than under static calculations and obtain either social and economical effect. The kinetic approach can also be used under the calculations of the critical fire load density in a compartment.

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